Mesozoic to Tertiary tectonic History of the Albanian ophiolites.

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Thematic Article

Mesozoic to Tertiary tectonic history of the Mirdita ophiolites, northern Albania

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Abstract In this paper, a summary of the tectonic history of the Mirdita ophiolitic nappe, northern Albania, is proposed by geological and structural data. The Mirdita ophiolitic nappe includes a subophiolite mélange, the Rubik complex, overlain by two ophiolite units, referred to as the Western and Eastern units. Its history started in the Early Triassic with a rifting stage followed by a Middle to Late Triassic oceanic opening between the Adria and Eurasia continental margins. Subsequently, in Early Jurassic time, the oceanic basin was affected by convergence with the development of a subduction zone. The existence of this subduction zone is provided by the occurrence of the supra-subduction-zone-related magmatic sequences found in both the Western and Eastern units of the Mirdita ophiolitic nappe. During the Middle Jurassic, continuous convergence resulted in the obduction of the oceanic lithosphere, in two different stages – the intraoceanic and marginal stages. The intraoceanic stage is characterized by the westward thrusting of a young and still hot section of oceanic lithosphere leading to the development of a metamorphic sole. In the Late Jurassic, the marginal stage developed by the emplacement of the ophiolitic nappe onto the continental margin. During this second stage, the emplacement of the ophiolites resulted in the development of the Rubik complex. In the Early Cretaceous, the final emplacement of the ophiolites was followed by the unconformable sedimentation of the Barremian–Senonian platform carbonate. From the Late Cretaceous to the Middle Miocene, the Mirdita ophiolitic nappe was translated westward during the progressive migration of the deformation front toward the Adria Plate. In the Middle to Late Miocene, a thinning of the whole nappe pile was achieved by extensional tectonics, while the compression was still active in the westernmost areas of the Adria Plate. On the whole, the Miocene deformations resulted in the uplift and exposition of the Mirdita ophiolites as observed today.

Key words: Mesozoic, Mirdita, northern Albania, obduction, ophiolites, tectonic, Tertiary.

INTRODUCTION

The interpretation of ophiolite sequences as on-land fragments of the oceanic lithosphere has originated a great number of models for their emplacement within or onto the continental lithosphere. Worldwide examples point out that one of the most common mechanisms for ophiolite emplacement is obduction (i.e. the thrusting of internally undeformed, huge slices of the oceanic lithosphere onto a buoyant continental margin; e.g. Dewey & Bird 1971; Gealy 1977; Coleman 1981; Moores 1982; Michard *et al*. 1991; Cawood & Suhr 1992; Searle & Cox 1999; Searle *et al*. 2004; and many others). Obduction is regarded as a multistage process involving intraoceanic detachments of ophiolite

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slab followed by thrusting onto a continental margin (intraoceanic and marginal stages according to Michard *et al.* 1991). The main feature of the obducted ophiolites is their occurrence as giant, undeformed nappes displaced far from their original setting and floating on a continental crust. However, some features of this process are still poorly understood, such as, for instance, the relationships among the subduction processes, the origin of the metamorphic sole and the timing of the deformations related to the emplacement onto the continental crust.

An exceptional opportunity to analyze the tectonic history of obducted ophiolites is provided by the Mirdita ophiolitic nappe from northern Albania. It is a good example of an obducted oceanic lithosphere derived from the eastern branch of the Mesozoic Tethyan oceanic basin, located between the Eurasia and Adria Plates. Different models for the geodynamic history of the Albanian ophiolites have been proposed recently (Collaku *et al.* 1991; Beccaluva *et al.* 1994; Shallo 1994; Kodra *et al.* 2000; Robertson & Shallo 2000; Bortolotti *et al.* 2002, 2004b; Hoeck *et al.* 2002; Saccani *et al.* 2004; Dilek *et al.* 2005), mainly based on petrological and/or stratigraphic data. Less attention has been paid to micro and mesostructural data derived from the ophiolitic sequences, even if this information is able to provide fundamental constraints for the reconstruction of their tectonic evolution.

In the present paper, a complete picture derived from a full integration of the geological and petrological features with the structural data is presented in order to outline the Mesozoic–Tertiary tectonic history of the Albanian ophiolites in the framework of the geodynamic evolution of the Hellenic–Dinaric Belt. In addition, this reconstruction is discussed to provide further insights for general models concerning the obduction of the ophiolites.

THE DINARIC–HELLENIC BELT

The Dinaric–Hellenic Belt (Fig. 1) is a north–south trending collisional chain of alpine age running from Slovenia and Serbia to southern Greece (Aubouin *et al.* 1970; Bernoulli & Laubscher 1972; Jacobshagen *et al.* 1978; Celet *et al.* 1980; Dimitrijevic 1982; Robertson & Dixon 1984; Smith 1993; Pamic *et al.* 1998; Robertson & Shallo 2000; Bortolotti *et al.* 2004b; and many others). This belt has traditionally been divided into four main tectonostratigraphic zones, each corresponding approximately to the modern concept of terranes. Each zone consists of an assemblage of variably deformed and metamorphosed tectonic units of oceanic and/or continental origin. These zones, from west to east, are (i) the deformed Adria zone; (ii) the external ophiolite belt; (iii) the Pelagonian–Korab–Drina–Ivanjica zone; and (iv) the Vardar zone. These zones are bounded to the west by the undeformed Adria zone and to the east by the Serbo–Macedonian–Rhodope Massif, generally regarded as the stable margin of the Eurasia Plate (Fig. 1).

The deformed Adria zone consists of a west-verging imbricate stack of tectonic units derived from the continental margin of the Adria Plate. These units are thrust onto the undeformed Adria margin. From west to east, this deformed zone is represented by the Ionian, Gavrovo (Kruja in Albania), Pindos (Krasta–Cukali in Albania) and Parnassos units. All these units are characterized by unmetamorphosed sequences, each including Triassic–Paleocene neritic and pelagic carbonate sequences topped by widespread Upper Cretaceous–Miocene siliciclastic turbidite deposits. The age of inception of the flysch deposition, which ranges from Late Cretaceous in the Pindos unit to Late Oligocene in the Ionian unit, is related to the westward migration of the deformation across the continental margin of the Adria Plate. In Montenegro, Bosnia, Croatia and Serbia, the deformed Adria zone is represented, from west to east, by the Budva, high Karst and pre-Karst units. Whereas the Budva unit can be regarded as the northward counterpart of the Pindos unit of Greece and Krasta–Cukali of Albania, the other units probably correlate to the Parnassos unit in Greece.

Eastward, the deformed Adria zone is thrust by the external ophiolite belt, represented by a huge oceanic nappe. This nappe is characterized by the occurrence of ophiolites ranging in age from Triassic to Jurassic, which are regarded as representative of the oceanic basin located east of the Adria Plate. This nappe consists of a stack of ophiolite units showing at their base a subophiolite mélange, consisting of an assemblage of continental- and oceanic-derived units. This mélange is known as the Advella mélange in Greece or the Rubik complex in Albania, whereas in Bosnia and Serbia it probably corresponds to the Bosnian–Durmitor unit. The external ophiolite belt is recognized as a continuous nappe from Argolis, Othrys, Pindos and Vourinous in Greece to Mirdita in Albania, Bistrica and Zlatibor in Serbia, and up to Krivaja in Croatia.

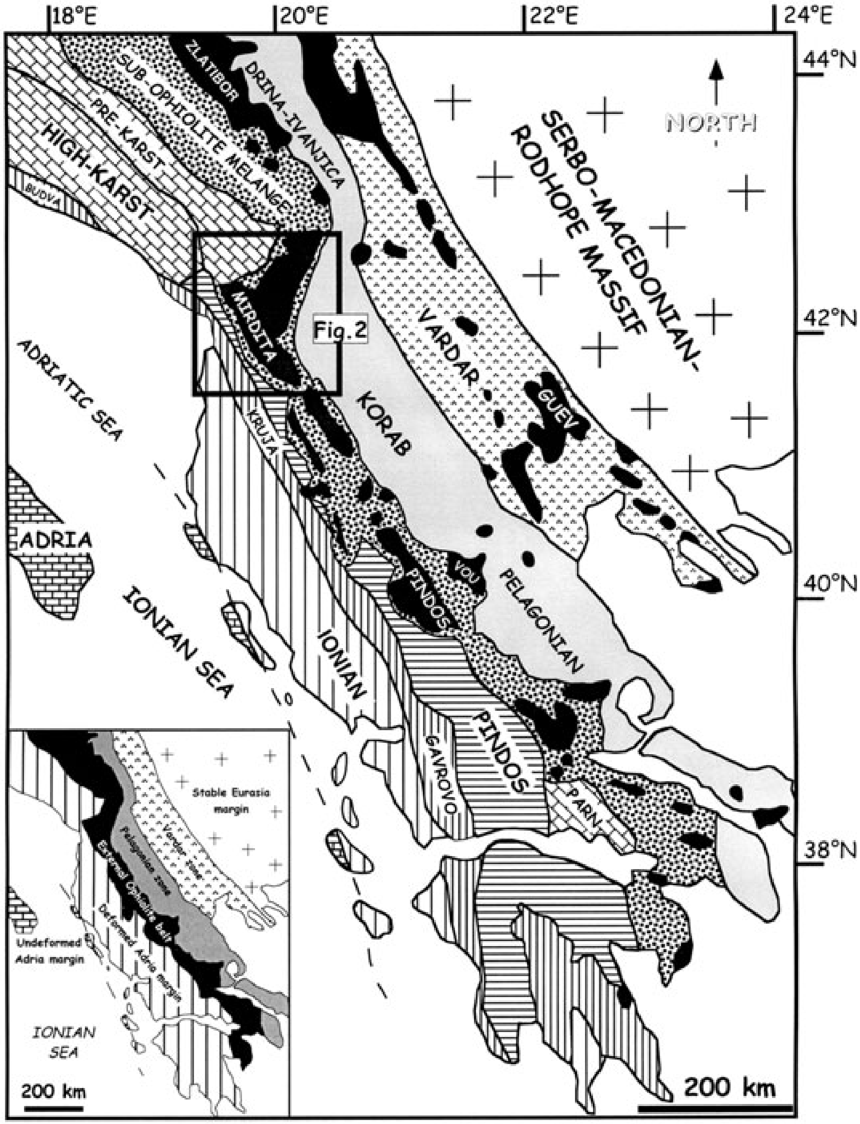

Fig. 1 Tectonic sketch of the Dinaric–Hellenic Belt with location of the major ophiolitic massifs (solid black), modified after Aubouin *et al.* (1970). Guev, Guevgueli; Oth, Othris; Parn, Parnassus zone; Vou, Vourinos. The location of Figure 2 is indicated in the boxed area.

In contrast, the Pelagonian–Korab–Drina–Ivanjica zone, hereafter simply referred to as the ‘Pelagonian’ zone, is represented by an assemblage of tectonic units consisting of a prealpine basement intruded by Upper Paleozoic granitoids and covered by Permian–Lower Triassic siliciclastic deposits, followed by Middle Triassic–Upper Jurassic carbonates. The units from the Pelagonian zone are regarded as being derived from the easternmost part of the Adria Plate (Bernoulli & Laubscher 1972; Zimmerman 1972; Vergely 1976; Jacobshagen *et al.* 1978; Collaku *et al.* 1992; Schermer 1993; Bortolotti *et al.* 1996, 2002, 2004b), or, alternatively, as belonging to a microcontinent between the Adria and Eurasia Plates (Jones & Robertson 1991; Shallo *et al.* 1992; Doutsos *et al.* 1993; Beccaluva *et al.* 1994; Ross & Zimmermann 1996; Kodra *et al.* 2000; Robertson & Shallo 2000; Dilek *et al.* 2005). Westwards, the Pelagonian units are thrust by the units belonging to the Vardar zone.

The Vardar zone is represented by a composite assemblage of continental and oceanic-derived units, including both Triassic and Jurassic ophiolites. The latter now represent a more internal ophiolite belt in the Dinaric–Hellenic chain.

The ophiolitic bodies constitute a semicontinuous ophiolite nappe from Greece to Macedonia, Serbia and Croatia. On the whole, the ophiolites in the Dinaric–Hellenic Belt mainly occur along two alignments (western, from Greece to Albania, Bosnia, Serbia and Croatia, and eastern from Greece to Macedonia and Serbia), with minor klippes between them.

The relationships between the ophiolitic units and the neighboring continental units are sealed by the deposits of the Meso-Hellenic trough, unconformably covering all of the nappe pile. These deposits, ranging in age from Eocene to Miocene, were sedimented in a northwest–southeast basin extending from southern Greece to northern Albania.

In all the proposed geodynamic models (e.g. Aubouin *et al.* 1970; Bernoulli & Laubscher 1972; Dimitrijevic 1982; Robertson & Dixon 1984; Smith 1993; Bortolotti *et al.* 1996, 2004b; Kodra *et al.* 2000; Robertson & Shallo 2000; Pamic *et al.* 2002; Dilek *et al.* 2005; and many others), the Dinaric–Hellenic Belt is regarded as the result of Mesozoic–Tertiary convergence and the subsequent continental collision developed as a result of the closure of the eastern branch of the Tethyan oceanic basin. This oceanic area opened following rifting along the northern margin of Gondwanaland from Late Permian?–Early Triassic time onwards. Subsequently, during Middle–Late Triassic time, the break-up led to the birth of an oceanic basin bordered by a pair of passive continental margins. The oceanic basin underwent convergence in the Early Jurassic as a result of motion between the Eurasia and Africa Plates. This convergence led to an intra-oceanic subduction associated with the development of a wide oceanic basin above the subduction zone. In the Middle Jurassic, the continuous convergence between the Eurasia and Adria Plates resulted in the obduction of ophiolites onto the Adria continental margin before the continental collision. After the continental collision up to the Neogene, the continuous convergence affected the continental margin of the Adria Plate, which was progressively deformed in west-verging, thick-thinned fold and thrust sheets represented by the Adria-derived units. In the resulting orogenic belt, the ophiolites of the Dinaric–Hellenic Belt are incorporated as huge thrust sheets floating above the continental margin-derived units.

GEOLOGICAL OUTLINE OF NORTHERN ALBANIA

Northern Albania is considered to be the western linkage between the Dinaric Belt and the Hellenic Belt (Aubouin *et al.* 1970). In this area (ISPGJ-IGJN 1983, 1985) three of the four tectonostratigraphic zones of the Dinaric–Hellenic Belt crop out (Figs 2,3): the deformed Adria zone, the external ophiolite belt and the Pelagonian zone (Meco & Aliaj 2000). Northern Albania is bounded southward by a narrow east–west trending area, known as the Vlora–Elbasan line (Nieuwland *et al.* 2001),

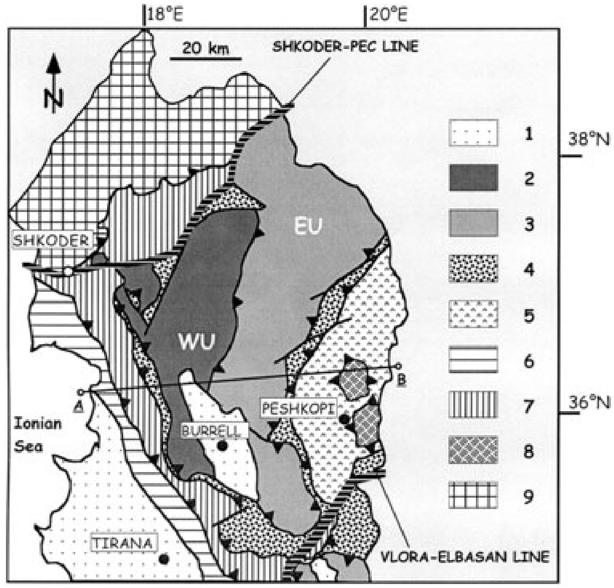

Fig. 2 Tectonic sketch of northern Albania. (1) deposits of Peri-Adriatic and Meso-Hellenic Trough; (2) Mirdita ophiolitic nappe, western unit (WU); (3) Mirdita ophiolitic nappe, eastern unit (EU); (4) Rubik complex; (5) units of the Pelagonian zone; (6) deformed Adria zone, Kruja unit; (7) deformed Adria zone, Krasta–Çucali unit; (8) units cropping out in the core of the Peshkopi and Sillatina tectonic windows; (9) deformed Adria zone, pre-Karts unit cropping out in the Albanian Alps. The line indicates the location of cross-section A–B represented in Figure 3; the Shkoder–Pec and Vlora–Elbasan lines are also indicated.

where erosion allows observation of the Krasta–Cukali unit cropping out below the Mirdita ophiolitic nappe. Northward, the boundary of northern Albania is represented by the Shkoder–Péc line (Dercourt 1967). This line, probably a paleo-transform fault, is regarded as a still active, strike-slip fault.

UNITS OF THE DEFORMED ADRIA ZONE

In northern Albania, the units of the deformed Adria zone are represented by the Kruja and Krasta–Cukali units, which crop out in the western areas (Figs 2,4). The succession of the Kruja unit (Robertson & Shallo 2000; and references therein) consists of Upper Cretaceous–Paleocene, shallow-water carbonates topped by Middle–Upper Eocene pelagic carbonates showing a transition to Upper Eocene–Miocene siliciclastic turbidites. At the top of the shallow-water carbonates, a stratigraphic hiatus has been identified. The Krasta–Cukali unit is in turn characterized by a succession consisting of Middle–Upper Triassic pelagic cherty limestones and radiolarites. At the top, Jurassic well-bedded, pelagic limestones and cherts and Lower–Upper Cretaceous deep-water carbonates occur. This succession is topped by

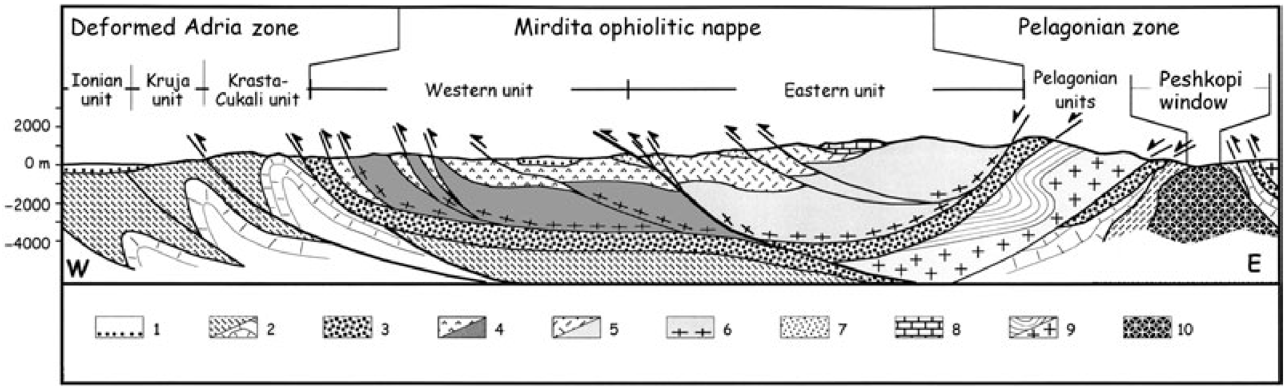

Fig. 3 Cross-section of northern Albania. See Figure 2 for the location of the cross-section (line A–B). (1) Deposits of Peri-Adriatic and Meso-Hellenic Trough; (2) units from deformed Adria zone (Krasta–Çucali and Kruja units; upper: the siliciclastic deposits; lower: the carbonate deposits); (3) Rubik complex and subophiolite mélange of the Peshkopi window; (4) western ophiolite unit (upper: crustal section; lower: mantle section); (5) eastern ophiolite unit (upper: crustal section; lower: mantle section); (6) metamorphic sole; (7) Simoni mélange and Firza flysch; (8) Barremian carbonate deposits; (9) units from Pelagonian zone (upper: sedimentary cover; lower: basement section); (10) Triassic evaporites of the Ionian unit cropping out at the core of the Peshkopi window.

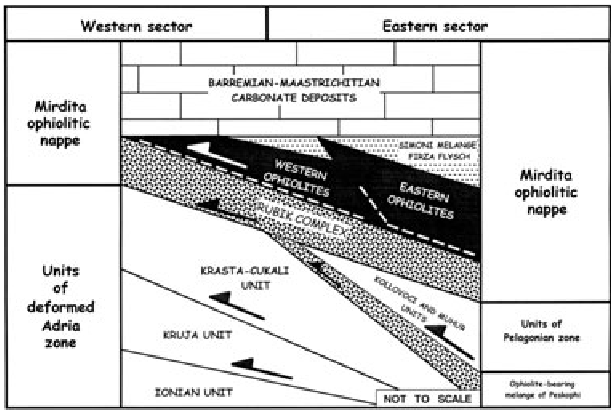

Fig. 4 Sketch showing the relationships among the tectonic units in northern Albania.

Maastrichtian–Upper Eocene siliciclastic turbidites. These units are deformed in a complex sequence of west-verging, north–south- to northeast–southwest-trending folds, developed under very low-grade metamorphic conditions. These folds are connected with a northeast–southwest- to north–south-trending, high-angle thrust characterized by brittle shear zones with a top-to-the-east shear sense (Fig. 3). This imbricate stack of thrust units developed from the Early Oligocene–Middle Miocene during the progressive migration of the deformation front toward the Adria Plate.

MIRDITA OPHIOLITIC NAPPE

The units from the deformed Adria zone are overlain by the Mirdita ophiolitic nappe (Meco & Aliaj 2000; and references therein). The boundary between these two units is represented by a west-verging, high-angle thrust. This nappe consists of two end-members (Fig. 4): the ophiolite units and the underlying Rubik complex (i.e. a subophiolite mélange; Bortolotti *et al.* 2004b; and references therein).

The Rubik complex (Bortolotti *et al.* 1996) consists of an assemblage of thrust slices derived from both continental and oceanic domains. In the geological literature, the Rubik complex is also reported as a 'carbonate periphery' or 'peripheral complex' (Shallo 1991, 1992, 1994; Kodra *et al.* 1993). The thrust slices are mainly represented by coherent sequences of continental and oceanic origin; however, slices made up of a sedimentary mélange, represented by blocks of carbonate, arenites and magmatic rocks set in a shaly or serpentinitic matrix, are common. The slices of continental origin generally consist of Triassic–Jurassic carbonate successions. According to Shallo (1991, 1992) and Kodra *et al.* (1993), the commonest succession consists of Middle Triassic cherty limestones grading upwards to Upper Triassic–Lower Liassic platform carbonates, topped by Middle–Upper Liassic, Ammonitico rosso-type nodular limestones and Dogger–Malm, pelagic cherty limestones and radiolarites (Kodra *et al.* 1993; Marcucci *et al.* 1994; Bortolotti *et al.* 1996). However, thick successions characterized by Middle Triassic–Malm pelagic deposits, represented by cherty limestones alternating with radiolarites, are also common. In addition, slices consisting of magmatic rocks covered by cherts of Anisian age (Kodra *et al.* 1993; Beccaluva *et al.* 1994; Bortolotti *et al.* 1996) have also been identified. These slices are characterized by pillow-lava picritic basalts, trachybasalts and trachytes showing within-plate to transitional geochemical affinity. However, the most widespread magmatic rocks are found as a slice at the top of the Rubik complex. These magmatic rocks, reported as a 'Volcano-sedimentary Formation' by Kodra *et al.* (1993) or the 'Porava Unit' by Bortolotti *et al.* (2004a), are represented of a sequence up to 500 m thick of pillow-lava basalts alternating with Middle–Late Triassic radiolarites and shales (Chiari *et al.* 1996). Geochemical data have revealed that the basalts are characterized by flat high-field-strength-element patterns and by slightly light-rare-earth-element depleted patterns, typical of present-day basalts generated at a mid-ocean ridge (Bortolotti *et al.* 2004a). In the Rubik complex, the other oceanic-derived slices, not thicker than 100 m, are represented by lherzolites, generally highly serpentinized. At the base of the Rubik complex, a 300-m-thick slice of ophiolite-bearing and carbonate turbidites of uppermost Tithonian–late Valanginian age occur. Slices of sedimentary mélange are represented by clasts of serpentinite, basalt, gabbro and sedimentary rocks set in a shaly or serpentinitic matrix of undetermined age. The deformation history of the Rubik complex, mainly developed in the volcano-sedimentary formation includes two superimposed folding phases developed under subgreenschist facies metamorphic conditions. The first phase is characterized by very tight to isoclinal folds associated with slaty cleavage. The subsequent deformation is represented by open to tight folds and a spaced crenulation cleavage.

The Rubik complex is thrust by two ophiolite units: the Western and Eastern units, according to their geological and petrochemical features (Shallo 1992; Shallo *et al.* 1992; Beccaluva *et al.* 1994; Bortolotti *et al.* 1996, 2002; Saccani *et al.* 2004). The boundary between these units is represented by the west-verging thrust developed during the Cretaceous tectonic events (Fig. 4).

The Western unit is characterized by a north–south-trending assemblage of thrust slices ranging in thickness from 100 to 700 m. The reconstructed stratigraphy (Fig. 5) includes, from bottom to top, the metamorphic sole, lherzolitic mantle tectonites, mafic–ultramafic cumulates, a discontinuous sheeted dyke complex and a volcanic sequence (Shallo 1991, 1994; Beccaluva *et al.* 1994; Bortolotti *et al.* 1996, 2002, 2004b; Saccani *et al.* 2004). However, the sheeted dyke complex as well as the gabbroic complex are generally lacking, and the crustal section can be only representative of the volcanic sequence (Cortesogno *et al.* 1998; Nicolas *et al.* 1999). The volcanic as well the intrusive sequence show high-Ti (mid-oceanic ridge basalt, MORB) affinity (Beccaluva *et al.* 1994; Bortolotti *et al.* 2002; Saccani *et al.* 2004). However, a volcanic sequence showing island arc tholeiites (IAT) and mid-ocean ridge (MOR)–IAT intermediate geochemical features directly overlying the more typical MORB sequences has been found (Bortolotti *et al.* 1996, 2002, 2004b; Saccani *et al.* 2004). In addition, boninitic dykes cutting the ophiolite sequence have also been discovered by Bortolotti *et al.* (2002). The radiolarian cherts, referred as Kalur cherts by Bortolotti *et al.* (1996),

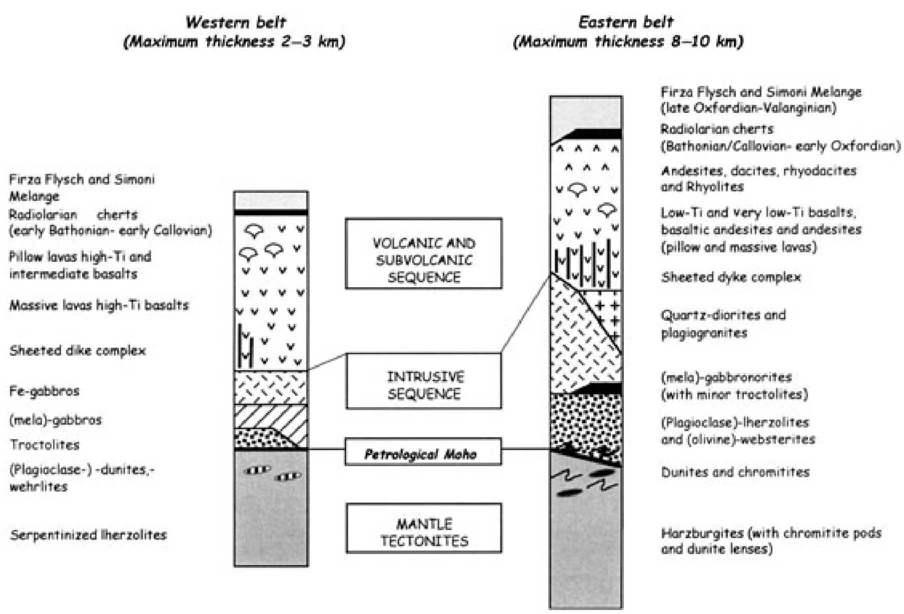

Fig. 5 Generalized stratigraphic sequences of the ophiolite sequences for the western and eastern units, Mirdita ophiolitic nappe (modified from Beccaluva *et al.* 1994).

found at the top of the IAT basalts, display radiolarian assemblages of late Bajocian/early Bathonian to late Bathonian/early Callovian age (Marcucci *et al.* 1994; Marcucci & Prela 1996).

The Eastern unit shows a sequence up to 10 km thick (Fig. 5), including, at the base, harzburgitic mantle tectonites with well-developed metamorphic sole at the base, a thick intrusive sequence, a sheeted dyke complex and a volcanic sequence (Shallo 1992, 1994; Shallo *et al.* 1992; Beccaluva *et al.* 1994; Hoxha & Boullier 1995; Bortolotti *et al.* 1996, 2002, 2004b; Robertson & Shallo 2000; Saccani *et al.* 2004). According to the geochemical data, the ophiolites from the Eastern unit show low-Ti affinity (Beccaluva *et al.* 1994; Saccani *et al.* 2004). These petrological features indicate that the origin of these ophiolites was in a supra-subduction zone (SSZ) setting (Beccaluva *et al.* 1994; Saccani *et al.* 2004). At the top of the pillow lava basalts, a sequence of radiolarites, referred to as Kalur cherts by Bortolotti *et al.* (1996), ranging in age from late Bathonian/early Callovian to middle Callovian/early Oxfordian has been recognized by Marcucci *et al.* (1994), Prela (1994) and Marcucci and Prela (1996). In addition, decimeter-thick sequences of cherts recognized in the uppermost part of the basalt flows show an upper Bajocian–lower Bathonian radiolarian assemblage (Chiari *et al.* 1994).

Both the ophiolite sequences from the Western and Eastern units are unconformably covered by a thick sedimentary sequence that includes the late Oxfordian to Tithonian Simoni mélange and the upper Tithonian to upper Valanginian Firza flysch (Bortolotti *et al.* 1996; Gardin *et al.* 1996). The Simoni mélange is a sedimentary mélange approximately 200–300 m thick, characterized by blocks ranging from several centimeters to several hundreds of meters in size, set in a shaly matrix. The blocks consists of continental-derived lithologies such as Permian sandstones, Triassic volcanics, Triassic cherts, Triassic–Liassic carbonates and minor metamorphic rocks (Shallo 1991; Bortolotti *et al.* 1996). The ocean-derived lithologies are represented by basalts, mantle ultramafics, gabbros and cherts derived from both western and eastern ophiolite sequences. The occurrence of layers of arenites in the uppermost levels of the mélange marks the transition to the Firza flysch. This formation is represented by turbidite deposits with ophiolite-bearing polimictic pebbly sandstones and mudstones at different stratigraphic levels. The ophiolite units and the Rubik complex are in turn unconformably covered by Barremian–Senonian, shallow-water carbonate deposits, with a thickness of up to 1500 m (ISPGJ-IGJN 1983, 1985).

UNITS OF THE PELAGONIAN ZONE

In the eastern area of northern Albania, the Mirdita ophiolitic nappe is overlain by units from the Pelagonian zone (Fig. 4). These units are characterized by a Paleozoic basement consisting of an Ordovician–Devonian sequence unconformably covered by a Permo-Triassic clastic sequence grading upward to Triassic and Jurassic neritic–pelagic, mainly carbonate, deposits (Robertson & Shallo 2000). In the Pelagonian zone, two main units, known as the Kollovoci and Muhur units, have been identified (Collaku *et al.* 1990). The Pelagonian units are deformed in a large antiform showing at its core several tectonic windows (Fig. 6), mainly in the Peshkopi and Sillatina areas, where a pile of tectonic slices crops out (Collaku *et al.* 1990, 1992). In the Peshkopi window, this pile includes, from top to bottom (Fig. 6): (i) a slice consisting of Upper Jurassic–Lower Cretaceous ophiolite-bearing mélange associated with huge serpentinites bodies; (ii) the Krasta–Cukali unit represented by a slice of Mesozoic carbonates; (iii) the Kruja unit represented by a slice consisting of siliciclastic turbidites of Oligo–Miocene age; and (iv) the Ionian unit represented by Triassic evaporites. The latter are dragged up in the footwall of a main thrust and remobilized as smeared-out surface extrusions at the core of the tectonic window (Velaj *et al.* 1999).

In the Peshkopi and Sillatina areas, a polyphase deformation history has been identified by Kilias *et al.* (2001). This deformation history includes two main deformation phases. The first deformation phase is characterized by asymmetric, overturned folds with a northeast–southwest trend associated with thrusts with a top-to-the-southwest sense of shear. Backthrusts with a top-to-the-northeast sense of shear and strike-slip faults have also been identified. This deformation phase is interpreted as having developed during the nappe stacking related to the progressive thrusting of the coupled Mirdita ophiolitic nappe and Pelagonian units onto the Krasta–Cukali, Kruja and Ionian units. This progressive thrusting is well defined by the age of the siliciclastic turbidites found at the top of the units derived from the Adria domain. According to the available data, this progressive thrusting ranges in age from Early Oligocene to Middle Miocene. This deformation phase can be compared

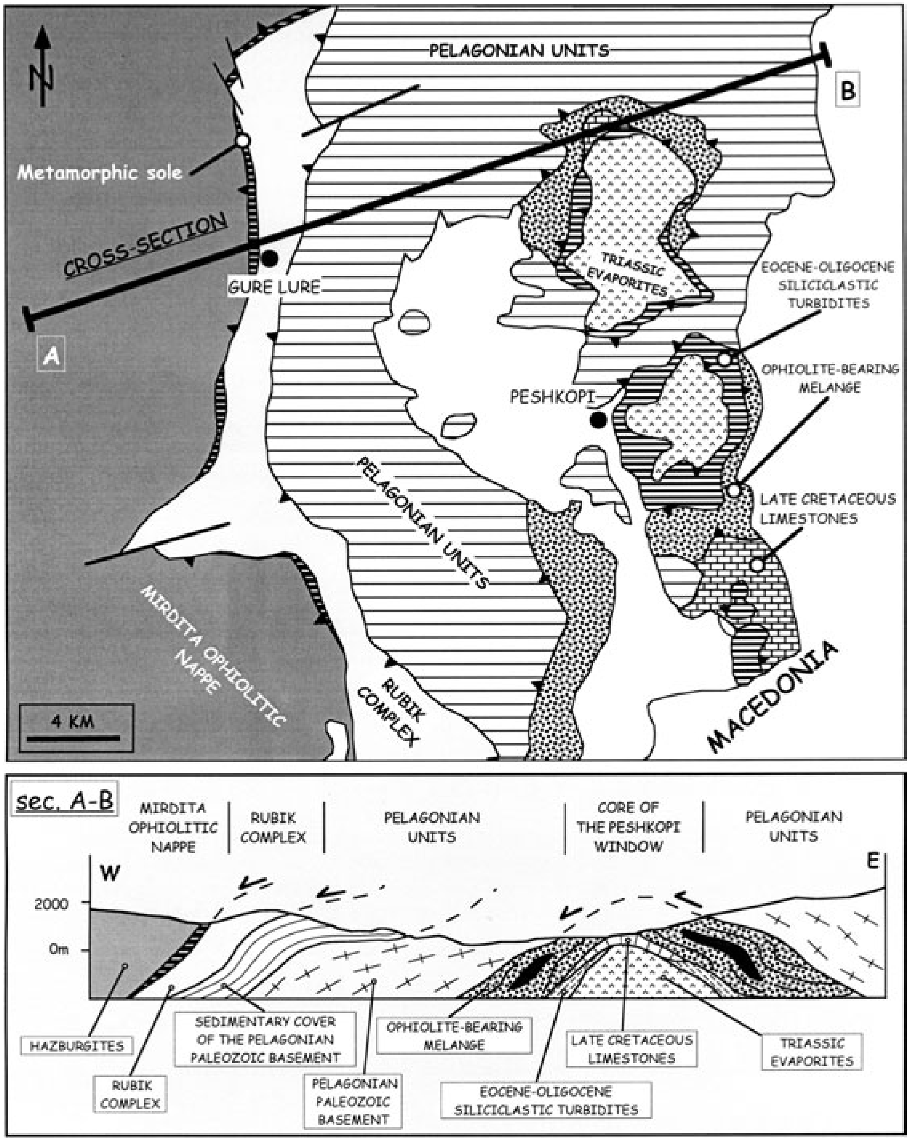

Fig. 6 Schematic geological map of the Peshkopi area and related cross-section.

with the deformations previously described in the units from the deformed Adria zone. The second deformation phase is characterized by northeast–southwest to NNE–SSW-trending, low-angle extensional shear zones that crosscut all the previous structures. These shear zones are brittle in the Mirdita ophiolitic nappe and in the Pelagonian units, whereas the underlying units show brittle–ductile features. In this frame, the older thrusts are reactivated as extensional faults with impressive thinning of the tectonic units developed during the previous phase. These structures are associated with northeast–southwest-trending, open folds with subhorizontal axial planes. This association of structures is coherent with extensional tectonics leading to the development of the Peshkopi and Sillatina tectonic windows, whereas the compression was still active in the more eastern areas. The second deformation phase, which affects all the units of the Peshkopi and Sillatina tectonic windows, is probably Middle to Late Miocene in age.

MESO-HELLENIC DEPOSITS

Finally, transgressive, marine–continental deposits of the Burrel Basin, belonging to the Meso-Hellenic trough, unconformably covered the structures of the Mirdita ophiolitic nappe (Fig. 4), including the Rubik complex as well as the Western and Eastern ophiolite units (ISPGJ-IGJN 1990). These deposits, ranging in age from Eocene to Miocene, are found as northwest–southeast-striking belts extending from southern to northern Albania (Fig. 2). In the easternmost areas, the nappe pile is unconformably covered by the Neogene 'molasse' deposits of the Peri-Adriatic trough (ISPGJ-IGJN 1990).

GEOMETRY AND KINEMATICS OF DEFORMATION IN THE OPHIOLITE SEQUENCE

As are all the other worldwide examples of obducted slices of oceanic lithosphere, the Mirdita ophiolites are characterized by deformations localized at the base of the mantle section – the metamorphic sole. The metamorphic sole developed during the intraoceanic stage of obduction, when a thick and hot section of oceanic lithosphere was detached and emplaced over the neighboring oceanic domain. The metamorphic sole originated at the base of the oceanic slice as a strongly deformed and metamorphosed shear zone. However, further deformations were acquired by the ophiolite sequence in the subsequent marginal stage, during its emplacement over the continental margin. These deformations are easily identified in the sedimentary cover of the ophiolites, mainly in the radiolarites that show pervasive deformation as folds and thrusts developed under very low-grade metamorphic conditions (Carosi *et al.* 1996b). Therefore both metamorphic sole and radiolarites represent suitable lithologies where the deformations, including folds, shear zones and foliations, can be analyzed in order to outline the tectonic evolution of the Mirdita ophiolitic nappe.

DEFORMATION HISTORY OF THE METAMORPHIC SOLE: INTRAOCEANIC STAGE-RELATED STRUCTURES

According to Collaku *et al.* (1991), Carosi *et al.* (1996a) and Dimo-Lahitte *et al.* (2001), the metamorphic sole of the northern Albanian ophiolites is characterized by an assemblage, up to 700 m thick, of garnet-bearing amphibolites, coarse- to fine-grained amphibolites, quarzites, garnet-bearing micaschists, calcschists, garnet-bearing paragneisses and minor mafic granulites. All these rocks are strongly deformed under high pressure/low temperature metamorphism. Based on their geochemical signature (Carosi *et al.* 1996a), the inferred protoliths for the amphibolites are basalts and gabbros, showing oceanic island basalt or MOR geochemical affinity, whereas quarzites, paragneisses and micaschists probably represent siliciclastic, deep-sea oceanic sediments. The rare layer of calcschists–impure marble can be interpreted as being derived from deep-sea carbonate turbidite. The metamorphic sole occurs below the peridotites, whose basal levels show obduction-related, low temperature mylonitic deformation (Hoxha & Boullier 1995; Rassios & Smith 2000). The metamorphic sole is in turn thrust onto the Rubik complex, mainly onto the volcano-sedimentary formation (Fig. 7a), where only sub-greenschist facies metamorphism has been detected (Carosi *et al.* 1996a). Where the relationships are well exposed, the boundary is represented by a shear zone up to 30–40 m thick characterized by cataclastic and ultracataclastic fault rocks derived from both the metamorphic sole and the volcano-sedimentary formation. In some places, the amphibolite facies metamorphic rocks can be found as boudinaged bodies inside the volcano-sedimentary formation. The amphibolites, the paragneisses and the micaschists display evidence of a polyphase deformation history that includes almost three phases developed under different pressure and temperature conditions. The structures of the D1 phase are recognized only in the thin sections of the coarse-grained amphibolites and paragneisses where relics of the S1 schistosity are preserved in the microlithons between the S2 schistosity. In thin sections, the S1 foliation is defined by coarse grains, oriented plagioclase and amphibole grains. The main deformation structures recognized at the mesoscale can be referred to the D2 phase. In all the outcrops, the main foliation is represented by the S2 schistosity (Fig. 7b), generally bearing well-defined L2 mineralogical lineations consisting of elongated fibers of amphibole or plagioclase, whereas in the gneisses and micaschists, the L2 lineations are represented by elongated fibers of white mica or oriented pressure shadows around garnets. Mineralogical lineations (Fig. 8) show WNW–ESE to northwest–southeast strikes in the western areas (Carosi *et al.* 1996a), whereas in the Eastern units, these lineations display northwest–southeast strikes (Collaku *et al.* 1992; Carosi *et al.* 1996a). In thin sections, the amphibolites are characterized by layers of plagioclase showing oriented granoblastic structure alternating to bands enriched in prismatic or acicular nematoblastic amphibole (tschermakitic hornblende to magnesium-hornblende) and clinopyroxene (diopside–salite) showing well-preferred orientation (Fig. 7c). In the granulites, the association of clinopyroxene and orthopyroxene with garnet and plagioclase is detected. The S2 schistosity in the paragneisses and micaschists is defined by oriented minerals of white mica (muscovite), biotite, plagioclase and garnet (almandine) (Fig. 7d,e). Decimeter-thick

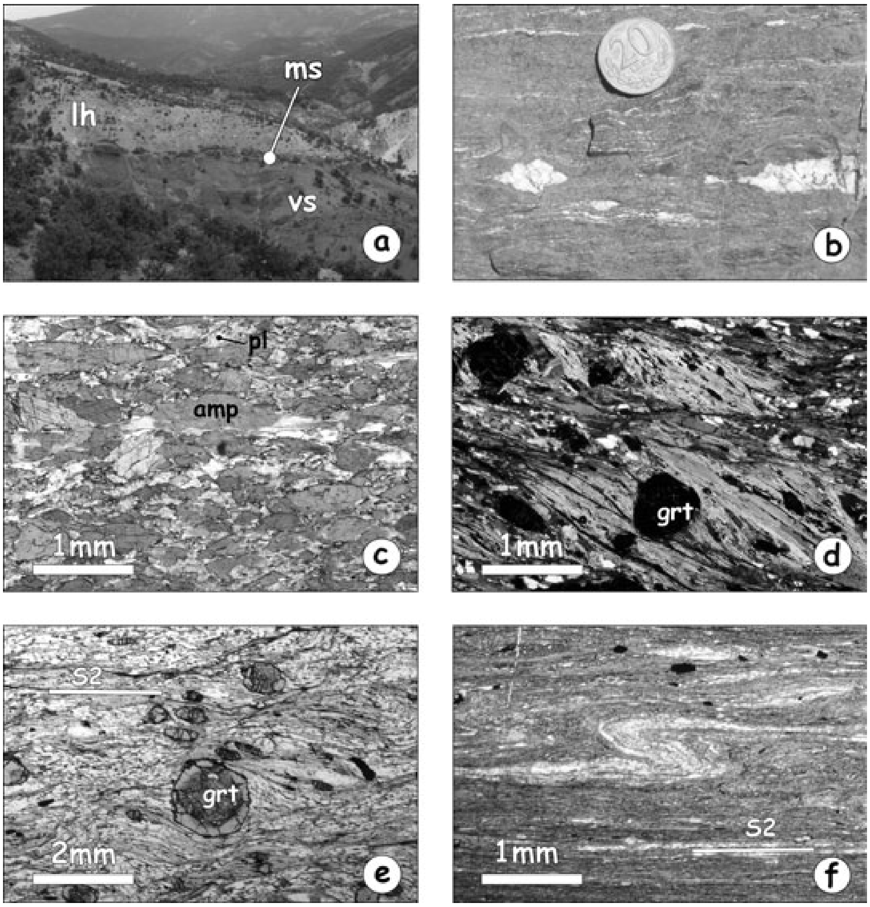

Fig. 7 The metamorphic sole of the Mirdita ophiolitic nappe. (a) View of contact among the lherzolites (lh), the metamorphic sole (ms) and the volcano-sedimentary formation (vs), western ophiolites, Gomsique Massif; (b) field occurrence of amphibolites with well-developed S2 foliation, Fushe Lura; (c) amphibolites characterized by bands enriched in prismatic or acicular nematoblastic amphibole (amp) showing oriented granoblastic structure alternating with layers of plagioclase (pl); (d,e) S2 schistosity in the paragneisses and micaschists defined by white mica (muscovite), quartz, plagioclase and garnet (grt); shear sense is indicated by S–C and s structures around garnet porphyroblasts; (f) mylonitic shear zones with intrafoliar folds indicating the shear sense.

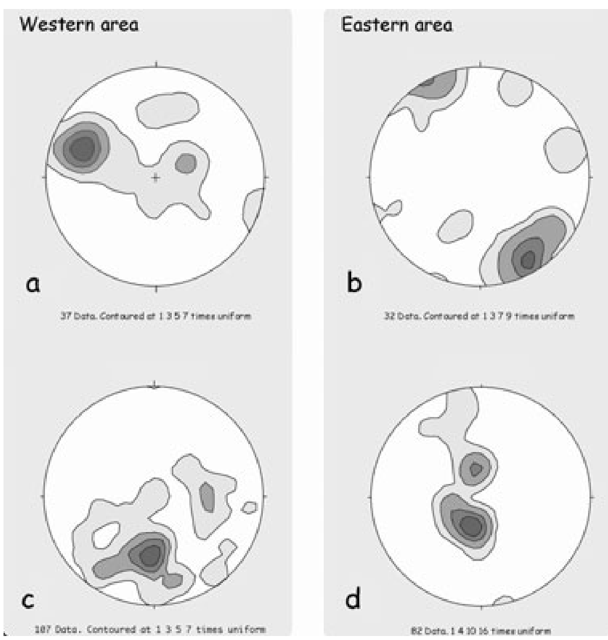

Fig. 8 Equal area, lower hemisphere stereographic representation of structural data from the metamorphic sole in western and eastern areas of the Mirdita ophiolitic nappe. (a,b) L2 mineral lineation; (c,d) S2 foliation.

mylonite shear zones with widespread kinematic indicators as intrafoliar folds (Fig. 7f) or σ structures are found parallel to the S2 schistosity in both amphibolites and paragneisses. The S2 schistosity is deformed by D3-phase structures. The D3 phase is mainly represented by F3 tight to isoclinal folds characterized by a northwest–southeast trend and steep axial plane. The associated foliation range from a well-developed crenulation cleavage in micaschists to a disjunctive cleavage in amphibolites and gneisses. Both in western and eastern areas, the F3 folds show an asymmetry coherent with a top-to-the-west or -southwest sense of shear. During the D3 phase, shear zones characterized by cataclastic structures are recognized.

According to Carosi *et al.* (1996a), different pressure–temperature (P–T) conditions of the metamorphism are recorded in slices of metamorphic sole. No differences for the P–T conditions of the peak metamorphism for the D1 and D2 phases have been reported. The related metamorphic overprint ranges from low (T = 680° ±20°C; P = 0.2–0.4 GPa) to intermediate (T = 740° ±25°C; P = 0.4–0.5 GPa) and high (T = 850° ±20°C;

$P = 0.4$–0.5 GPa) temperature amphibolite facies (Carosi *et al.* 1996a). In addition, a granulite facies metamorphism ($T = 800$–$860°C$; $P = 0.9$–1.1 GPa) is reported by Dimo-Lahitte *et al.* (2001). However, data about high pressure values are still scarce and contrast with the majority of the analyses performed on the amphibolites, which indicate $P < 0.5$ GPa. In addition, the granulites from the Mirdita metamorphic sole are characterized by the occurrence of orthopyroxene (Dimo-Lahitte *et al.* 2001), the lack of which is a diagnostic feature for high pressure granulites (O'Brien & Rotzler 2003). On the whole, the granulite as well the amphibolites seem to have originated at a pressure of <0.5 GPa. A retrograde, low-grade metamorphism associated with chevron folds is also recorded. It is very important to underline that all the samples clearly show evidence of amphibolite–granulite facies metamorphism. So, a major jump of metamorphic grade can be identified between the metamorphic sole and the underlying volcano-sedimentary formation, where only a subgreenschist metamorphic mineral assemblage has been detected (Carosi *et al.* 1996a). In addition, the results of structural and petrological analyses show that the tectonic setting of the metamorphic sole from the Albanian ophiolites consists of an assemblage of multiple slices, each with a different P–T metamorphic climax, without evidence of a clear inverse zonation of the metamorphism. The occurrence of slices with different metamorphisms is a common feature in the metamorphic sole, as recognized, for instance, by Hacker and Mosenfelder (1996) in the Oman ophiolite.

The kinematic indicators from the metamorphic sole of the Western ophiolite unit clearly reveal a top-to-the-west sense of shear (Carosi *et al.* 1996a). The same structural elements in the eastern metamorphic sole provide contrasting kinematics. According to Collaku *et al.* (1991) and Carosi *et al.* (1996a), the sense of shear is top-to-the-west, whereas Dimo-Lahitte *et al.* (2001) indicate a coexistence of top-to-the-west and top-to-the-east indicators, with the latter prevailing. This contrasting evidence can be explained with a deformation where simple and pure shear coexisted. In this frame, the kinematic indicators identified within the mylonitic shear zones developed during the amphibolite metamorphism can provide more valuable data. In the eastern metamorphic sole, these shear zones provide evidence for a top-to-the west sense of shear (Fig. 7f). Ar–Ar dating ranging from 159 ± 2.6 to 171.7 ± 1.7 Ma by step-heating of mineral concentrates, laser-probe step-heating and spot fusions on single grains (amphiboles and micas) from the metamorphic sole is provided by Dimo-Lahitte *et al.* (2001), without sharp differences between the Western and Eastern units. These datings can be interpreted as the age the metamorphism developed during the intraoceanic stage of obduction.

DEFORMATION HISTORY OF THE RADIOLARITES: MARGINAL STAGE-RELATED STRUCTURES

The tectonic setting of the Western unit is represented by an imbricate stack of thrust sheets, showing a thickness ranging from 1 to 2 km. These sheets are mainly composed of mantle ultramafics with remnants of the metamorphic sole at their base. However, sheets represented either by basalts with the associated sedimentary sequence, mainly consisting of Kalur cherts, the Simoni mélange and the Firza flysch, or by layered and/or isotropic gabbros are also common. Each thrust sheet displays an internal structure characterized by minor folds. The related deformation history has been reconstructed in the Kalur cherts by Carosi *et al.* (1996b). Structural analysis revealed a polyphase deformation history, with two phases of folding followed by faulting events. The first folding D1 phase, identified only in the Kalur cherts, consists of recumbent, tight to very tight F1 folds with geometry ranging from similar to parallel (Fig. 9a). The A1 axes are moderately scattered with a cluster between N120E/N150E (Fig. 10). The associated S1 axial plane foliation has been identified as disjunctive cleavage, mainly developed by a pressure solution mechanism (Fig. 9b). The D2 phase, which also affects the Simoni mélange and the Firza flysch, is marked by overturned, asymmetric F2 folds with concentric geometry. The F2 folds, characterized by axes ranging from N100E to N130E (Fig. 10), show a short overturned limb associated with steep to gently sloping axial planes. The F2 folds are associated with southwest- to south-verging and northwest- to north-trending thrusts. Associated with the thrust systems, northwest–southeast- to northeast–southwest-trending strike-slip faults are recognizable at the map scale. The vergence of the F1 and F2 folds as well as the kinematics along the thrust planes is from southwest to west in both the Western and Eastern units. On the basis of structural evidence, the D1 phase predates the deposition of the Simoni mélange. The timespan for this phase is presently estimated to be between the age of the top of the Kalur cherts (early Callovian) and the base of the Simoni mélange (Tithonian). According to Carosi *et al.* (1996b), the D1 phase recognized in the Kalur cherts can be related to the inception of the ophiolites emplacement onto the continental margin. The last deformation event is represented by the second D2 phase recognized in the Kalur cherts, which also affected the Simoni mélange and Firza flysch. This phase, which probably marked the final stage of emplacement of the Albanian ophiolites onto the continental margin, developed in the Hauterivian. The sedimentation gap recognized between the Firza flysch and the shallow-water Barremian–Senonian carbonate sequence, which are unaffected by the folding phases, can be related to the D2 phase.

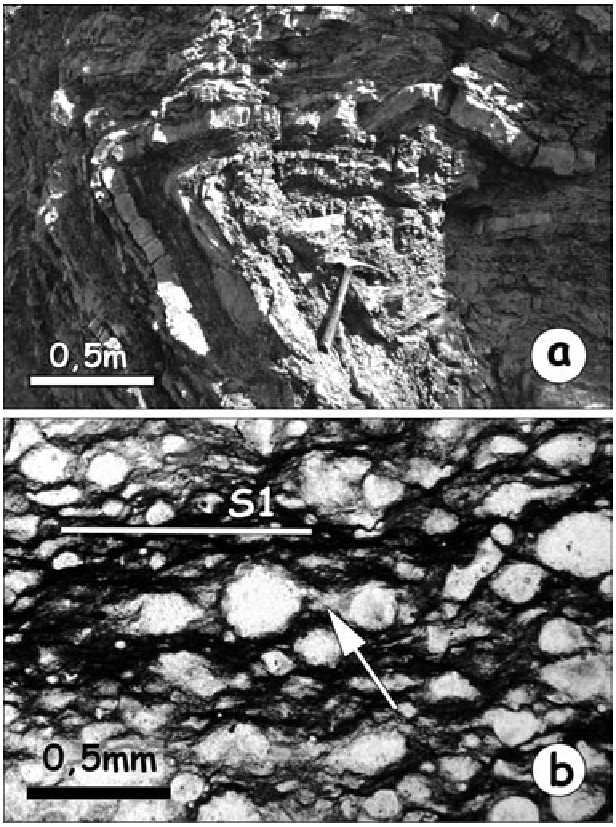

Fig. 9 Photographs of structures recognized in the Kalur Cherts. (a) tight parallel F1 folds; (b) S1 axial plane foliation highlighted by pressure solution surfaces and by recrystallization of quartz fibers around radiolarian (arrow).

RECONSTRUCTION OF THE TECTONIC HISTORY OF THE ALBANIAN OPHIOLITES

Some remarks about the geological history follow, in order to provide valuable tools for the reconstruction of the tectonic evolution of the Mirdita ophiolitic nappe.

AGE OF THE OCEANIC BASIN

In the Rubik complex, the occurrence of Middle–Upper Triassic MOR basalts, associated everywhere with slices of lherzolite, suggests that the phases of oceanization had already been reached in the Albania area during the Middle Triassic, probably after a rifting phase developed in the Early Triassic (Bortolotti *et al.* 2004a). This finding is confirmed by the occurrence of Middle–Late Triassic, Early Jurassic and Middle Jurassic MOR basalts reported by Bortolotti *et al.* (2002) in the Dhimaina ophiolite sequence, Argolis Peninsula, which represent the southward extension of the Pindos, Vourinos and Koziakas ophiolites (Bortolotti *et al.* 2004b). In contrast, the SSZ ophiolites from the Mirdita nappe are Middle Jurassic in age, according to the age of the radiolarites found in (late Bajocian–early Bathonian) or at the top of (late Bajocian–early Bathonian to middle Callovian–early Oxfordian) the IAT basalts (Bortolotti *et al.* 1996; and references therein). On the whole, the MOR oceanic lithosphere is Middle–Late Triassic in age according to evidence from the Rubik complex, whereas the SSZ oceanic lithosphere is Middle Jurassic in age as detected in both the Western and Eastern units of the Mirdita ophiolitic nappe.

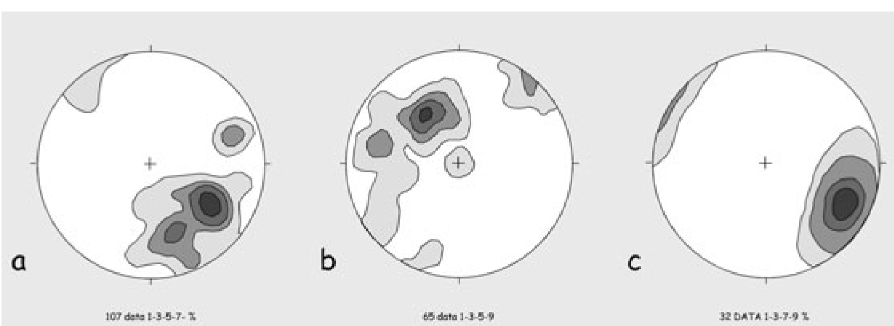

Fig. 10 Equal area, lower hemisphere stereographic representation of the structural data from the Kalur cherts. (a) A1 axes; (b) S0 bedding; (c) A2 axes.

GEODYNAMIC SIGNIFICANCE OF THE MOR AND SSZ OPHIOLITES FROM THE MIRDITA NAPPE

The Middle–Upper Triassic basalts found in the Rubik complex represent the remnants of a MOR oceanic lithosphere without the influence of a subduction-related magmatism (Bortolotti *et al.* 2004b). In addition, the western ophiolites are representative of a MOR oceanic lithosphere, but the occurrence of intermediate MOR–IAT, IAT basalts and boninites indicates that the oceanic basin, from which these ophiolites were derived, has experienced two different stages of crustal growth (Bortolotti *et al.* 1996, 2002; Bébien *et al.* 1998, 2000). In the first stage, a MOR-type oceanic lithosphere was generated at a mid-ocean ridge spreading center. Subsequently, during the second stage, a portion of this lithosphere was trapped in the supra-subduction setting (most probably in a proto-forearc region) with consequent generation of intermediate MOR–IAT and IAT basalts as well as boninitic dykes. In order to explain the coexistence of these geochemically different magma groups, Bortolotti *et al.* (2002) have proposed a model based on the complexity of the magmatic processes that may take place during the initiation of a subduction in the proximity of an active mid-ocean ridge. This model implies that the initiation of subduction processes close to an active mid-ocean ridge leads to contemporaneous eruptions in a forearc setting of MORBs generated from the extinguishing mid-ocean ridge, and of intermediate MOR–IAT basalts generated in the SSZ mantle wedge from a moderately depleted mantle source. The development of the subduction in a young, hot lithosphere caused the generation of IAT basalts and boninites from strongly depleted mantle peridotites in the early stages of subduction, soon after the generation of intermediate MOR–IAT basaltic rocks. On the whole, the western ophiolites can be interpreted as a MOR oceanic lithosphere trapped over a subduction zone and subsequently affected by subduction-related magmatism (Bortolotti *et al.* 2002, 2004b). In contrast, the eastern ophiolites represent an oceanic lithosphere entirely developed in an SSZ (Beccaluva *et al.* 1994; Saccani *et al.* 2004). The same age of the IAT basalts in the Eastern and Western units, as demonstrated by the radiolarian assemblage found in the radiolarites (Marcucci & Prela 1996), indicates these sequences originated in the same oceanic basin in Middle Jurassic time. This oceanic basin, located over a subduction zone, was therefore characterized by a trapped MOR lithosphere where a younger oceanic lithosphere, originated entirely in a supra-subduction setting, was emplaced.

AGE OF THE SUBDUCTION INCEPTION

If the Albanian ophiolites are representative of a basin located in a supra-subduction setting in Middle Jurassic time, not older than Bajocian–Bathonian (Bortolotti *et al.* 1996), subduction of an older oceanic crust is required to produce IAT magmatism. Assuming that a timespan of 10–15 Ma from the inception of subduction is required to develop the SSZ magmatism, the convergence should have started during the Early Jurassic (Bortolotti *et al.* 2004b). No clear evidence for the dipping of this subduction is available. However, the occurrence of calcoalkaline magmatic rocks of Late Jurassic age in the Vardar zone (Bebien *et al.* 1986), eastward of the present-day location of the Mirdita ophiolites, suggests an east-dipping of the subduction. Therefore, in the proposed evolution (Fig. 11), a subduction characterized by the underthrusting of the oceanic lithosphere below the Eurasia Plate is assumed. However, the high angle of rotation proposed for the Dinaric–Hellenic Belt in the Jurassic–Neogene timespan (Kondopolou 2000) implies that the direction of the Jurassic subduction cannot be regarded as coinciding with the present-day trend of the ophiolites from the Dinaric–Hellenic Belt.

AGE OF OBDUCTION

The age of the inception of the obduction process is well constrained by the age of the amphibolites from the metamorphic sole. The Ar–Ar radiometric datings of the amphiboles from the northern Albanian metamorphic sole range from 159 ± 2.6 to 171.7 ± 1.7 Ma (Dimo-Lahitte *et al.* 2001). Therefore, the intraoceanic stage of the obduction started in the Middle Jurassic and developed up to earlier Late Jurassic time. Despite problems regarding the correlations between the paleontological and radiometric ages, these data point to an inception of convergence in the oceanic basin slightly older than the magmatic events, as detected in other examples of obducted ophiolites (e.g. the Oman ophiolites; Michard *et al.* 1991).

EVIDENCE FROM THE INTRAOCEANIC STAGE OF OBDUCTION

The stage of intraoceanic thrusting is recorded by the occurrence of slices of metamorphic sole at

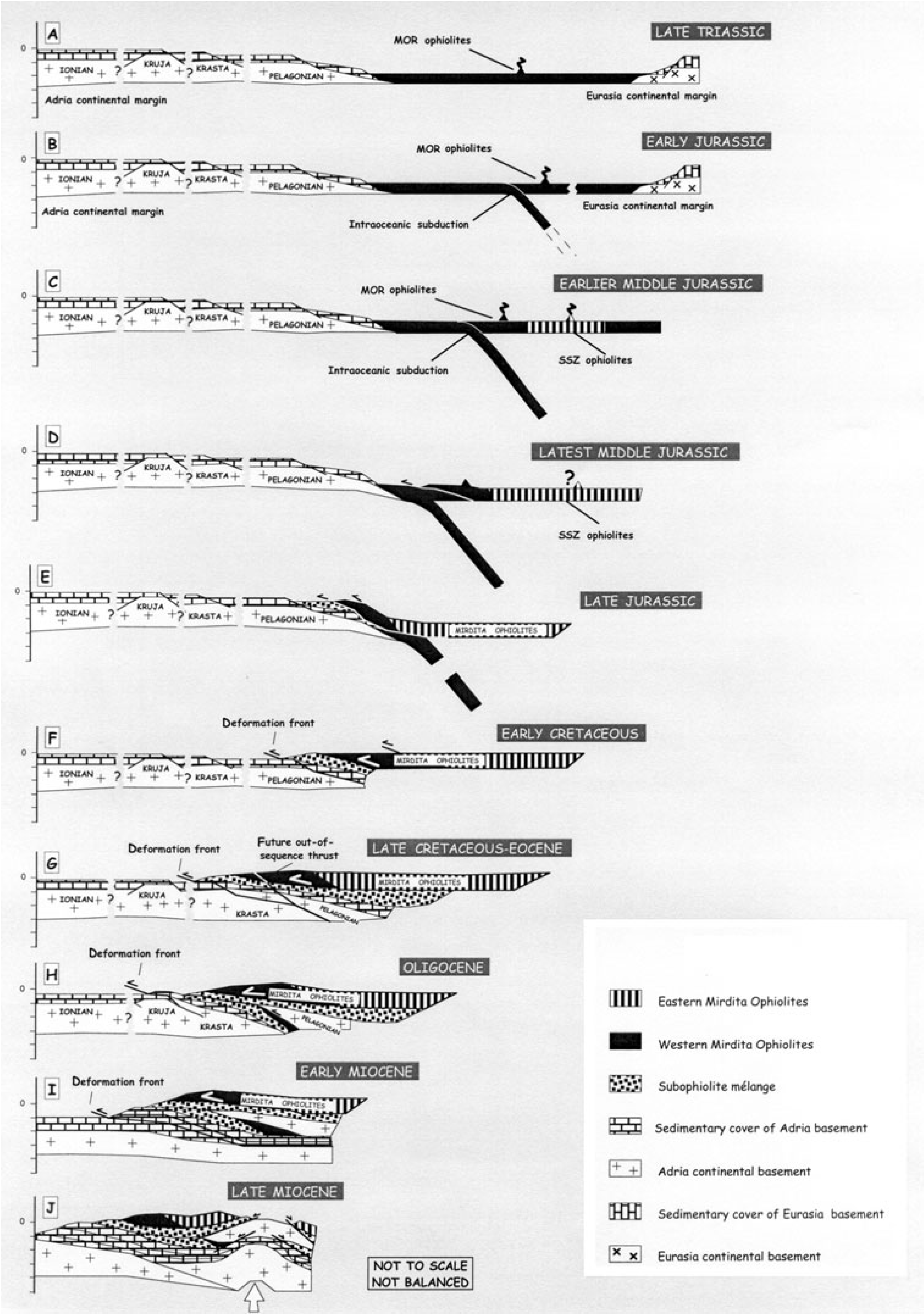

Fig. 11 2-D sketch illustrating the different steps (from A to J) of the tectonic evolution proposed for the Mirdita ophiolitic nappe in the Mesozoic–Tertiary timespan. MOR, mid-ocean ridge.

the base of the mantle ultramafics in both the Western and Eastern ophiolites (e.g. Collaku *et al.* 1992; Shallo 1992; Carosi *et al.* 1996a; Dimo-Lahitte *et al.* 2001). The metamorphic sole consists of an assemblage (up to 700 m thick) of ocean-derived rocks metamorphosed under climax P–T conditions related to granulite and amphibolite facies (Carosi *et al.* 1996a; Dimo-Lahitte *et al.* 2001). No rocks showing greenschist facies climax metamorphism have been found in the metamorphic sole. Tectonic models indicate that the high temperature required for the development of the metamorphic sole could have been produced in the shear zone formed at the base of an overridden section of oceanic lithosphere (McCaig 1981, 1983; Michard *et al.* 1991; Cawood & Suhr 1992; Suhr & Cawood 1993; Searle & Cox 1999; Searle *et al.* 2004). The occurrence of different P–T conditions of peak metamorphism in the different slices can be interpreted as being related to the origin of the metamorphic sole by a tectonic assemblage of slices developed at different stages and assembled in a single body during the thrusting of the ophiolites (Hacker & Mosenfelder 1996). In order to explain the very high geothermal gradient suggested by the occurrence of the amphibolite and granulite metamorphism, a source of heat is required. Residual heat from a young and still hot oceanic lithosphere could have supported the temperatures required for the metamorphism that developed during the obduction process. Recent models have regarded the obduction process located in the lower plate during its underthrusting in a flattening subduction zone (Dimo-Lahitte *et al.* 2001). However, the very high geothermal gradient is inconsistent with a subduction process where the metamorphisms are characterized by high pressure conditions. Therefore, the geochemical features of the Mirdita ophiolites, that indicate their location is in an SSZ, as well as the tectono-metamorphic features of the metamorphic sole, are coherent with the location of the obduction process in the upper plate over a subduction zone, where young and a still hot oceanic lithosphere was affected by compression immediately after their origin. In addition, the metamorphic sole can provide evidence for the kinematics of the ophiolite emplacement. The L2 mineral lineations show WNW–ESE to northwest–southeast strikes in western areas (Carosi *et al.* 1996a), whereas in eastern areas these lineations display strikes ranging from east–west to northwest–southeast (Collaku *et al.* 1992; Carosi *et al.* 1996a). On the whole, the structural data suggest that the displacement during the intraoceanic stage ranged from east–west to northwest–southeast. In turn, the shear sense detected in the amphibolites determined on the microstructures related to amphibolite facies metamorphism is recognized in both the Western and Eastern ophiolite units as top-to-the-west or to-the-northwest (Collaku *et al.* 1992; Carosi *et al.* 1996a).

ORIGIN OF THE RUBIK COMPLEX

The Rubik complex originated during the marginal stage as the result of the emplacement of the obducted oceanic lithosphere onto the continental margin (Bortolotti *et al.* 1996, 2004b). During this emplacement a wedge consisting of slices detached from their continental basement developed at the base of the obducted oceanic lithosphere. The result of this process is a tectonic wedge – the Rubik complex – sandwiched between the obducted ophiolites and the underlying continental margin. This interpretation is suggested by the tectonic setting of the Rubik complex and its features, as, for instance, the occurrence of slices consisting of carbonate successions representative of the continental margin where the ophiolites were emplaced. However, oceanic slices have also been identified. These slices can probably be interpreted as remnants of an older, pre-existing accretionary wedge, developed during the Lower Jurassic subduction. In this hypothesis, the accretionary wedge was enclosed in the Rubik complex during the displacement of the obducted oceanic lithosphere towards the continental margin, as suggested by Bortolotti *et al.* (2004b). Many of the oceanic and/or continental sequences were contemporaneously deformed and eroded during the main tectonic stage – the shedding of blocks, particularly from their basal levels, lead to the formation of a true sedimentary mélange, which was subsequently incorporated as slices into the Rubik complex. The origin of this complex can therefore be regarded as the result of a mixing between tectonic and sedimentary processes that took place during the ophiolite emplacement onto the continental margin in Late Jurassic time. During these events, the lithologies from the Rubik complex were deformed under a subgreenschist facies metamorphism. Further thrusts occurred during the subsequent Lower Cretaceous intracontinental deformation; during these stages, slices of upper the Tithonian–Upper Valanginian ophiolite-bearing mélange were accreted to the slice of carbonate sequences, leading to the present-day setting of the Rubik complex.

INTERPRETATION OF THE SIMONI MÉLANGE AND FIRZA FLYSCH

The first deformation event recognized in the Kalur cherts is followed by the sedimentation of the Simoni mélange and Firza flysch (Shallo 1991; Bortolotti *et al.* 1996; Gardin *et al.* 1996). The large-scale unconformity at the base of the Simoni mélange, above the cherts, as well as the pillow lava and massive basalts, are recognized throughout the Mirdita region (Bortolotti *et al.* 1996). This suggests that the deposition of the mélange was associated with an important submarine erosion phase of the underlying deposits. In addition, the sedimentation of the Simoni mélange, as well as that of the Firza flysch, corresponds to a sharp inception of turbiditic debris flows and slide deposits derived from both oceanic and continental source areas. These features suggest that the Simoni mélange, as well as the Firza flysch, are probably the sedimentary response to the main tectonic stage that affected the Albanian ophiolites. The involvement of the neighboring continental margins in this stage is suggested by the diffuse occurrence of continental-derived blocks in the Simoni mélange, as well as by the debris composition of the Firza flysch. This tectonic-related sedimentation began during the Tithonian and continued until late Valanginian. The origin of the Simoni mélange and Firza flysch is still a matter of debate. Robertson and Shallo (2000) have proposed for these deposits an origin connected with mud-diapir(s) along large-scale faults in the ophiolitic nappe, where fragments of the Rubik complex were dragged up to the top of the ophiolitic nappe. An alternative explanation (Bortolotti *et al.* 2004b) is represented by a thrust located in the inner part of the ophiolitic nappe and able to expose the Rubik complex and the underlying continental margin (i.e. the source areas of the Simoni mélange and Firza flysch). Recently, Dilek *et al.* (2005) have proposed a source area of the Simoni mélange and Firza flysch in correspondence with a tectonic wedge related to eastward emplacement of the Mirdita ophiolitic nappe. Despite these suggestions, the origin of these deposits still represents an open problem. However, all the interpretations about the origin are able to explain the stratigraphic features detected in these deposits, such as, for instance, the Triassic volcanics and Triassic–Liassic carbonates, analogous to that recognized in the underlying Rubik complex.

THE CARBONATE SEQUENCES AT THE TOP OF THE MIRDITA OPHIOLITES

The final emplacement of the Mirdita ophiolitic nappe is followed by the unconformable sedimentation of the Barremian–Senonian, mainly shallow-water carbonate deposits at the top of the ophiolitic nappe. The age of these deposits confirms that the emplacement of the ophiolitic nappe was completed in Early Cretaceous time and, from the Late Cretaceous onwards, the convergence mainly affected the Adria continental margins. These deposits, as well as the overlying Meso-Hellenic deposits, are affected by brittle deformations as inverse and normal faults (Kilias *et al.* 2001). These deformations can be regarded as the result of the Lower Oligocene–Middle Miocene tectonics connected with the thrusting of the coupled Mirdita ophiolitic nappe and Pelagonian units over the Krasta–Cukali, Kruja and Ionian units and later extensional tectonics.

TECTONIC SIGNIFICANCE OF THE PESHKOPI AND SILLATINA WINDOWS

The occurrence of the Peshkopi and Sillatina tectonic windows, and the same structures along the Shengerij corridor clearly demonstrate that the present-day tectonic setting of northern Albania is the result of a large-scale, westward thrusting of the coupled Mirdita ophiolitic nappe and Pelagonian units onto the units of the deformed Adria zone (i.e. the Ionian, Kruja and Krasta–Cukali units; Collaku *et al.* 1990, 1992; Kilias *et al.* 2001). This thrusting developed from the Early Oligocene to the Middle Miocene, according to the age of the turbidites at the top of the Krasta–Cukali, Kruja and Ionian units. In addition, the structures identified in the Peshkopi and Sillatina tectonic windows provide evidence for extensional tectonics that affected the eastern areas of northern Albania in the Middle–Late Miocene timespan. The result of these extensional tectonics, characterized by folds and shear zones, is a strong modification the previous structural setting.

EVIDENCE FOR AN EVENT OF OUT-OF-SEQUENCE THRUSTING IN THE PESHKOPI AND SILLATINA TECTONIC WINDOWS

The occurrence of a slice consisting of Upper Jurassic–Lower Cretaceous ophiolite-bearing mélange associated with serpentinite bodies between the Pelagonian and the Krasta–Cukali units is a puzzling feature detected in the Peshkopi and Sillatina tectonic windows. This feature can be interpreted as result of an event of out-of-sequence thrusting in Miocene time. The proposed reconstruction includes (i) the thrusting of the coupled Mirdita ophiolitic nappe and Pelagonian units onto the Krasta–Cukali unit in Early Oligocene time; and (ii) the subsequent out-of-sequence thrust that affected the advancing front of the Mirdita ophiolitic nappe (i.e. the Upper Jurassic–Lower Cretaceous ophiolite-bearing mélange and the associated serpentinite bodies), today found in the Peshkopi and Sillatina tectonic windows. This event could have produced a tectonic structure where the Krasta–Cukali unit and the oceanic-derived slices are thrust by the Pelagonian units with the Mirdita ophiolitic nappe at the top.

A MODEL FOR THE TECTONIC HISTORY OF THE ALBANIAN OPHIOLITES

Different models have been proposed for the tectonic evolution of the Albanian ophiolites (see Shallo & Dilek 2003 for a complete review). These models (Collaku *et al.* 1991; Beccaluva *et al.* 1994; Shallo 1994; Kodra *et al.* 2000; Robertson & Shallo 2000; Bortolotti *et al.* 2002, 2004b; Saccani *et al.* 2004; Dilek *et al.* 2005) show relevant differences, mainly concerning the features of the Triassic–Early Cretaceous geodynamic history.

For instance, the rifting processes related to the opening of the oceanic basin, from which the Mirdita ophiolitic nappe was derived, are generally reported as Early Jurassic in age by most researchers. However, Bortolotti *et al.* (2004b) have proposed an Early Triassic age for the rifting process, based on new geochemical and paleontological evidence. In addition, different interpretations have been proposed about the paleogeographic location of the oceanic basin in Jurassic time. Most authors (Beccaluva *et al.* 1994; Shallo 1994; Kodra *et al.* 2000; Robertson & Shallo 2000; Saccani *et al.* 2004; Dilek *et al.* 2005) suggest a location between the Adria and Pelagonian Plates (i.e. in the same position as the present-day Mirdita nappe). However, other authors (Collaku *et al.* 1991; Bortolotti *et al.* 2004b) suggest an original location east of the Pelagonian zone (i.e. in the Vardar domain), mainly through structural evidence. In these interpretations, the emplacement of the Mirdita ophiolitic nappe is the result of a large-scale displacement toward the Adria Plate. Another matter of debate is represented by the dipping of the subduction during the Late Jurassic–Early Cretaceous timespan. Generally, this subduction zone has been envisaged as being westward dipping below the Pelagonian or Eurasian Plate (Collaku *et al.* 1991; Beccaluva *et al.* 1994; Shallo 1994; Kodra *et al.* 2000; Bortolotti *et al.* 2002, 2004b). However, recent models have proposed a dip of the subduction below the Adria Plate (Robertson & Shallo 2000; Saccani *et al.* 2004; Dilek *et al.* 2005). In contrast, there is a general agreement on the dipping of the subduction zone in Tertiary time about a westward dipping subduction zone. Finally, the sense of shear during the obduction of the ophiolites is also under discussion. Most authors suggest a bi-divergent model (Beccaluva *et al.* 1994; Shallo 1994; Kodra *et al.* 2000; Robertson & Shallo 2000; Saccani *et al.* 2004) with a coeval opposite sense of shear on both the western and eastern sides of the Mirdita ophiolitic nappe. Alternatively, other authors have proposed a westward (Collaku *et al.* 1991; Bortolotti *et al.* 2002, 2004b) or eastward sense of shear (Dilek *et al.* 2005).

Taking into account all the models discussed previously, a tentative reconstruction of the tectonic history of the Albania ophiolites in the Mesozoic–Tertiary timespan is provided here, mainly based on geological and structural data about the Mirdita ophiolitic nappe, as well as evidence derived from the underlying units of the Pelagonian and deformed Adria zones. A sketch of this evolution is shown in Figure 11.

- The history started in Triassic time, as suggested by the occurrence of Triassic MOR basalts in the Rubik complex. This occurrence provides the evidence for an oceanic basin already having opened between the Adria and Eurasia Plates in Middle Triassic time. This oceanic basin developed through a Lower Triassic rifting stage, the evidence of which is preserved in the carbonate slices of the Rubik complex, where pelagic succession of Triassic age is recognized. The phase of spreading continued from Middle to Late Triassic (stage A in Fig. 11) according to the age of radiolarites associated with MOR basalts in the Rubik complex.
- Subsequently, in Early Jurassic time (stage B in Fig. 11), the oceanic basin was affected by convergence, when a subduction zone developed as result of the sharp change in the motion between the Adria and Eurasia Plates. The

existence of this subduction zone is provided by the occurrence of the SSZ-related magmatic sequences found in the Western and Eastern units of the Mirdita ophiolitic nappe, where upper Bajocian–lower Bathonian cherts intercalated in IAT basalts have been found. In the SSZ, coexistence of a MOR oceanic lithosphere with SSZ magmatism has been found in the Western unit of the Mirdita nappe (Bortolotti *et al.* 1996, 2002; Hoeck *et al.* 2002; Saccani *et al.* 2004). This MOR lithosphere is regarded as being trapped in the SSZ basin (most probably in a proto-forearc region) with consequent emplacement of intermediate MOR–IAT and IAT basalts, as well as boninitic dykes.

- In the same basin, the SSZ lithosphere of the Eastern unit was generated at a subsequent stage of the subduction process (stage C in Fig. 11). On the whole, all the Jurassic ophiolites from northern Albania represent a composite oceanic crust belonging to the same oceanic basin (i.e. a supra-subduction basin), which experienced two different accretion events, in a mid-ocean ridge spreading center and, subsequently, in a supra-subduction setting. According to Dewey (1980), the process of the opening of an oceanic basin in a supra-subduction setting can be regarded as the result of the roll-back of the hinge zone belonging to the down-going plate. When the rate of the roll-back is higher than that of plate convergence, the extension in the supra-subduction takes place with the opening of an oceanic basin (e.g. Beccaluva *et al.* 2004; Dilek *et al.* 2005). Therefore, the resulting picture for the earlier Middle Jurassic timespan includes an oceanic basin located eastwards of the Adria Plate and characterized by a subduction zone separating the lower plate with a MOR oceanic lithosphere, today preserved only in the Rubik complex, from an upper plate where a trapped MOR oceanic lithosphere coexisted with the SSZ lithosphere.
- During the Middle Jurassic, the continuous convergence between the Adria and Eurasia Plates resulted in the obduction of the SSZ oceanic lithosphere; this event was probably connected with the involvement of the continental crust in the subduction zone. This event produced a sharp decrease of the rate for the roll-back of the down-going plate that became lower than the rate of the plate convergence. Subsequently, the transfer of the compression in the SSZ leading to the inception of the obduction process occurred (stage D in Fig. 11). According to Michard *et al.* (1991), the obduction process consists of two different stages – the intraoceanic and marginal stages. The intraoceanic stage is characterized by the thrusting of a section of oceanic lithosphere over the neighboring one. The development of high-grade metamorphic rocks (i.e. the amphibolites and the granulites) occurs in correspondence with the high-temperature shear zone between the two sections of the young and still hot oceanic lithosphere. According to radiometric dating, this stage occurred from 159.0 ± 2.6 to 171.7 ± 1.7 Ma (i.e. from the Middle Jurassic to the earlier Late Jurassic; Dimo-Lahitte *et al.* 2001). The sense of shear indicators collected in the metamorphic sole from both the Western and Eastern units provided evidence for a displacement from east to west or from southeast to northwest during the intraoceanic thrusting. According to Collaku *et al.* (1992), this evidence suggests that the paleogeographic location of the Jurassic oceanic basin was eastward of the Pelagonian zone, which can be interpreted as the easternmost portion of the Adria Plate. In this frame, the Mirdita ophiolites were derived from an oceanic domain eastward of the Adria Plate. Probably, the roots of this oceanic basin are located in the Vardar zone or at its boundary with the Serbo–Macedonian–Rhodope Massif. For instance, Brown and Robertson (2004) suggested a configuration of the Vardar zone with two oceanic basins of different ages. In their hypothesis, the easternmost oceanic basin of Jurassic age can be regarded as the area from which the Albanian ophiolites were derived. This oceanic basin, probably totally destroyed in the Early Cretaceous, was separated from the westernmost oceanic basin by a continental microplate where a magmatic arc was emplaced. This basin developed in Late Jurassic time and definitively closed only in Early Tertiary time, as suggested, for example, by Pamic *et al.* (2002).
- In the Late Jurassic (stage E of Fig. 11), the marginal stage developed by the emplacement of the ophiolitic nappe onto the continental margin (Shallo 1991, 1992, 1994; Kodra *et al.* 1993; Bortolotti *et al.* 1996; Robertson & Shallo 2000). As for the worldwide examples of obducted ophiolites (e.g. Dewey & Bird 1971; Gealy 1977; Coleman 1981; Moores 1982; Michard *et al.* 1991; Cawood & Suhr 1992; Searle & Cox 1999; Searle *et al.* 2004; and many others), the Mird-

ita ophiolitic nappe is characterized by well-preserved sequences unaffected by the ductile and pervasive deformations and related metamorphism. All the obduction-related deformations are accumulated in the metamorphic sole and the original features of the Western and Eastern ophiolitic units remain slightly modified. The result of this continental margin emplacement is a tectonic wedge (i.e. the Rubik complex), consisting of continental- and oceanic-derived slices detached during the emplacement of the ophiolite nappe and sandwiched between the obducted ophiolites and the continental margin. The origin of this complex is probably a multistage process, with interference of sedimentary and tectonic events. The occurrence of ophiolite slices involved in the complex is a puzzling feature. They can be interpreted as remnants of an older, pre-existing accretionary wedge developed during the Lower to Middle Jurassic subduction. In this hypothesis, the accretionary wedge was enclosed in the Rubik complex during the progressive displacement of the ophiolitic nappe towards the continental margin. If the ophiolitic nappe was derived from an SSZ basin, as testified by the geochemical affinity of the intrusive and magmatic sequences, part of the accretionary wedge, developed in correspondence with the subduction zone, can be deformed and partially enclosed at the base of the ophiolitic nappe during its displacement. During this second stage, a basin filled by ophiolite-bearing deposits (i.e. the Simoni mélange and the Firza flysch; Gardin *et al.* 1996) developed at the top of the ophiolitic nappe. In the Early Cretaceous, the emplacement of the ophiolites onto the easternmost area of the Adria continental margin, today represented by the units from the Pelagonian zone, was completed.

- The final emplacement of the ophiolites is marked by the unconformable sedimentation of the carbonate deposits at the top of the ophiolitic nappe. The Barremian age of these deposits confirms that the emplacement of the ophiolitic nappe was ultimated in the Early Cretaceous (stage F in Fig. 11).
- Subsequently, from the Late Cretaceous onward (stage G in Fig. 11), the compression-related deformation was transferred to the Adria continental margin. This progressive deformation, which affects the units derived from the deformed Adria zone, is well represented by the shifting in the age of the turbidites at the top of the successions as well as the time of the inception of the deformation in each unit.
- The Maastrichtian–Upper Eocene turbidites from the Krasta–Cukali unit represent the first foredeep deposits, subsequently deformed in the Early Oligocene (stage H in Fig. 11).
- The second foredeep is represented by the Upper Eocene–Lower Miocene turbidite deposits from the Kruja unit, in turn deformed in the latest Early Miocene (stage I in Fig. 11). Probably, the Lower Miocene deformation was associated by an out-of-sequence thrust, the evidence for which is provided by the tectonic setting of the Peshkopi windows, where slices of ophiolite-bearing deposits are sandwiched between the Krasta–Cukali and Pelagonian units. In this frame, the thrusts recognized in the Meso-Hellenic deposits at the top of the Mirdita ophiolitic nappe can be related to this out-of-sequence thrust event. In the same timespan, the Pelagonian units are thrust by the continental and oceanic units from the Vardar zone, which represents a suture where the Albanian ophiolites were derived (Collaku *et al.* 1992). On the whole, the progressive thrusting from the Late Cretaceous to the Early Miocene produced an imbricate stack of tectonic units at the front (i.e. at the western side) of the Mirdita ophiolitic nappe (Fig. 3). The progressive eastward thrusting into the Adria domain is characterized by the steepening of the thrust developed in the first stage of the intracontinental deformation. This process can explain the occurrence of very steep, up to vertical attitude, thrusts among the ophiolitic units, the Rubik complex and the Krasta–Cukali units, as depicted in Figure 3.
- In the Middle to Late Miocene (stage L in Fig. 11), a thinning of the whole nappe pile was achieved by extensional tectonics, while the compression was still active in the westernmost area of the Adria Plate. The extensional tectonics mainly resulted in the exhumation of the Ionian, Kruja and Krasta–Cukali units as observed today at the core of the Peshkopi and Sillatina windows, regarded here as first-order extension-related deformation structures. The normal and reverse faults related to the Miocene deformations are also recognized in the Mirdita ophiolites (Kilias *et al.* 2001). On the whole, the Miocene deformations resulted in the uplift and exposition of the Mirdita ophiolites as observed today.

CONCLUSIONS

The Mirdita ophiolitic nappe preserves the records of a long-lived, Triassic–Miocene history of a fragment of the eastern branch from the Tethyan oceanic basin, located between the Adria and Eurasia continental margins. This basin was originated by a Lower Triassic rifting phase, followed by a Middle Triassic spreading phase, leading to a wide area characterized by a MOR oceanic lithosphere. This oceanic basin was affected in Early Jurassic time by convergence, with the development of a subduction zone, probably dipping below the Eurasia Plate. During the Middle Jurassic, the subduction processes resulted in the development of a wide SSZ characterized by an SSZ oceanic lithosphere. The continuous convergence resulted, in the latest Middle Jurassic, in the obduction of the ophiolites, represented by the Mirdita ophiolitic nappe. The collected data confirm that the obducted ophiolites are representative of a section of SSZ oceanic lithosphere deformed when it was young and still hot, immediately after the end of the magmatic processes. The obduction occurred in the upper plate of the subduction zone, probably characterized by a dipping below the Eurasia Plate. This geodynamic frame is analogous to that of the SSZ ophiolites from Oman, Cyprus, Newfoundland, etc. Different from these examples, the Albanian ophiolites provide evidence for the involvement in the obduction process of MOR ophiolites, as detected in the Western units. However, the Western ophiolites can be interpreted as representative of a trapped oceanic crust in an SSZ geodynamic setting. This confirms that all the obducted ophiolites were derived from an SSZ geodynamic setting. According to Michard *et al.* (1991), the obduction history developed through two steps, referred to as the intraoceanic and marginal stages. During the intraoceanic stage, the metamorphic sole developed at the base of the Albanian ophiolites, represented by a level of oceanic-derived rocks up to 700 m thick, highly deformed under amphibolite and granulite facies metamorphism. This metamorphism is associated with a polyphase ductile history developed at high geothermal gradient, as expected for an intraoceanic thrusting of hot oceanic lithosphere. During the intraoceanic stage, the deformation is localized only at the base of the overriden section of oceanic lithosphere. In contrast, in the marginal stage, the deformation is brittle and affects the whole ophiolite sequence, from mantle to sedimentary cover. In the Albanian ophiolites, the marginal stage-related deformations are represented by a polyphase history developed by thrusts and folds under very low-grade metamorphic conditions, as detected for the Kalur cherts. The marginal stage is interpreted as the result of the thrusting onto the continental margin of a cold oceanic lithosphere. On the whole, the deformations detected in the Albanian ophiolites are mainly referred to the obduction history, from the intraoceanic to the marginal stage. However, the Albanian ophiolites provide evidence for a large-scale displacement without strong internal deformations during the post-obduction history. This displacement was acquired during the intracontinental convergence, by Upper Cretaceous–Miocene compressive and extensional events. After these events, the Mirdita ophiolites acquired their present-day tectonic setting – that is, a giant oceanic nappe floating over the units derived from the Adria Plate.

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